Proposal to the WWRP/WGNE

THe **O**bserving System **R**esearch and **p**redictability **ex**periment

THOR*pex*

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Proposal[1] to the WWRP/WGNE

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Project Overview

The skillful prediction of high-impact weather remains one of the greatest scientific and societal challenges of the 21st century. Despite advances in forecast skill over the last decades, limitations in observing coverage, data assimilation methods, and model formulation restrict the rate of progress in improving weather prediction. The Observing System Research and Predictability Experiment (THOR*pex*) is a ten-year international research program to accelerate improvements in short-range (up to 3 days) and medium-range (3 to 10 day) deterministic and probabilistic (ensemble) predictions and warnings of high-impact weather over the Northern Hemisphere. The weather events to be considered include systems of mid-latitude, arctic, or tropical origin, are primarily synoptic-scale, and often contain significant embedded mesoscale features. THOR*pex* will examine predictability and observing systems issues, and establish the potential to produce significant statistically-verifiable improvements in forecasts of high-impact weather. The program builds upon and coordinates with the advances being made in the operational forecasting and basic-research communities.

[1] A list of persons who participated in meetings and discussions that contributed to the writing of this proposal appears on page 20.

To achieve its objectives, THOR*pex* will:

- Perform observing-system experiments with real and "virtual" observations to determine optimal observing and data assimilation strategies for improved predictions of high-impact weather. Contribute to the development of new and innovative operational data assimilation systems and model parameterizations.
- Conduct diagnostic studies of analyses and forecasts of life-cycles of high-impact weather systems that are difficult to predict. Identify inter-annual and intra-seasonal large-scale flow regimes that produce weather events with low predictive skill and high societal and economic impacts.
- Establish the relative importance of model formulation and initial condition error in producing forecast errors at various forecast lead-times.
- Test the ability of advanced ensemble forecast systems to more accurately predict the probability of high-impact weather events.
- Identify geographical regions where new permanent observing systems would provide the greatest improvement to Northern Hemispheric forecasts. Develop improved strategies for targeting *in-situ* and satellite observing systems. A special focus will be on cloudy regions where current-generation satellite data are limited in vertical resolution.
- Conduct an ambitious field campaign to enhance the operational observing system. The THOR*pex* Hemispheric Field Campaign will last for at least a season, but preferably up to one year. It will provide operational and research data sets to evaluate the performance and forecast impacts of enhanced observing and data assimilation systems. In preparation for this Campaign, regional experiments will be carried out to address specific predictability issues and to test new observing and data assimilation systems.
- Determine the economic and societal benefits derived from improved forecasts of high-impact weather. Assess whether permanent improvements to the operational weather prediction system, suggested by THOR*pex* research, would justify the additional costs.

- Collaborate with regional and global programs that require observations in remote and data-sparse regions (WSR, TAMEX-II, PACJET, CLIVAR), and with programs to validate and calibrate satellite observations (NAST-I, SSMIS) .
- Provide guidance to agencies responsible for the design of the permanent and targeted components of the regional and global observing system, including EUCOS and NAOS.

1. Background

Major failures in forecasts of high-impact weather arise from a combination of inaccurate initial conditions[2] and errors in model formulation (model error). The relative importance of these error sources as a function of forecast lead-time remains an open question, as the two sources are inter-dependent and difficult to separate. Forecast models are continually being improved through better physical parameterizations, increased resolution, and other upgrades. However, many large forecast errors still result from initial condition errors. For example, the analyzed initial positions of synoptic trough and ridge systems over wide areas of the North Pacific Ocean can be in error by as much as several hundred kilometers on certain days, which has a major impact on short and medium-range forecasts for the northern Hemisphere.

Recent examples of high-impact weather events that were not well-forecast, on the short and medium-range, include the series of violent storms striking western Europe in December 1999, and the U.S. East Coast major snow storm in January 2000. Such extreme events cause great costs to society through damage to property, loss of life, and disruption of shipping, aviation, energy management, and agriculture. Improved numerical forecasts will help reduce the societal costs of high-impact weather events by providing government agencies and the general public with the most accurate information possible on all forecast time scales.

[2] Initial conditions (the model “analysis”) are produced by data assimilation procedures, and are used to start a numerical weather forecast model.

The goals of THOR*pex* are aligned with the mission of weather services throughout the world to improve operational numerical weather prediction (NWP). From the North American perspective, the National Weather Service (NWS), the USWRP (Schlatter *et al*. 1999), and NAOS have identified forecast improvement goals for rapidly-developing coastal and continental winter storms, arctic cold-air outbreaks, extreme precipitation events, and land-falling tropical cyclones. Achieving these goals will require optimal use of existing and anticipated satellite data, creative new approaches to *in-situ* observing, advanced methods for data assimilation, improved numerical models, and increases in computing capability.

High-impact weather systems of particular interest for European nations include smaller scale and rapidly developing cyclones, high precipitation events, and zones of very high surface wind-speeds. European nations recognize that additional upper-air and surface observations over the North Atlantic are required to improve short-range weather forecasts (Graham et al. 2000). In north-western Europe, polar lows create forecast difficulties for fishing and shipping. EUCOS is conducting limited trials of remotely-piloted aircraft observations over the north Atlantic sector early in 2002. The quantity of upper-air soundings over Russia has declined, and it is recognized that attention needs to be given to restoring this capability.

Key forecast objectives for Asian nations include improved predictions of tropical cyclones, extreme precipitation events associated with disturbances along the Meiyu front, and cold-air outbreaks during winter monsoon events. Ongoing efforts by Asian nations to test new observing systems (e.g., driftsondes, remotely-piloted aircraft) over the western Pacific, East China Sea, and Siberia, can be advanced with international coordination under the framework of THOR*pex*

Substantial upgrades to the global satellite network will be made during the next decade. The new satellite platforms will include advanced sensors capable of observing several thousand channels, compared to current systems that observe less than one hundred. These new satellite observations are expected to improve the quality of the initial conditions in numerical weather forecast models. However, even with the addition of these more advanced sensors, it will still be necessary to consider supplemental observations at certain times and in certain regions. For example, current satellite observations are limited in cloud-covered regions, which are highly correlated with initial condition sensitivity (McNally 2000). Supplemental observations may also be needed over land and sea-ice surfaces.

Diagnostic studies show that initial condition errors in dynamically active, data-sparse regions are a frequent cause of short-range forecast error (Klinker et al. 1998). For example, the largest 72-hr forecast errors occurring over western (Fig. 1) and eastern (Fig. 2) North America during three winters (1997-1999), respectively, can be traced to initial condition errors (primarily, poor upper-air temperature and wind analyses) over regions of the North Pacific and arctic North America. The largest 96-hr forecast errors over western Europe (Fig. 3) during January and February 1999 were most sensitive to initial conditions over portions of Canada. In these examples, the adjoint of a numerical forecast model is used to give a first-order estimate of forecast error sensitivity to initial conditions.

Inter-annual and intra-seasonal variations in large-scale flow regimes modulate the source regions for initial condition and forecast errors. During the most recent La Niña winter (1999), the largest 72-hr forecast errors over eastern North America were sensitive to initial condition errors in a region of the eastern Pacific between Hawaii and Alaska (Fig. 2a). During the El Niño winter of 1998, the most sensitive region was adjacent to the U.S. West Coast (Fig. 2b). Shapiro et al. (2000) note that short-range forecast errors during the El Niño winter (1998) were smaller on average than in the La Niña winter (1999), and that changes in forecast error source regions are likely related to variations in baroclinic life cycles modulated by the El Niño-Southern Oscillation (ENSO).

Recent field programs in which upper-air coverage was selectively improved by targeting observations in sensitive data-sparse regions include: i) the Fronts and Atlantic Storm-Track Experiment (FASTEX, Joly *et al*. 1999), ii) the North Pacific Experiment

(NORPEX, Langland *et al*. 1999), and iii) the Winter Storm Reconnaissance program (WSR, Szunyogh *et al*. 2001). These programs demonstrated that short-range forecast errors in selected winter-season cases can be reduced by providing reconnaissance aircraft dropsondes and additional satellite observations. It has also been shown that the impact of targeted observations on forecast skill depends strongly on the data assimilation procedure and level of background error (Bergot 2001). THOR*pex* will extend the accomplishments of FASTEX, NORPEX, and WSR to the more general problem of testing a wide range of observing systems, using advanced targeting methods and data assimilation procedures in all relevant regions of the northern hemisphere.

Forecast verification in THOR*pex* will primarily be on synoptic-scales, using analyzed fields produced from data provided by the operational observing network supplemented by the field campaigns of THOR*pex*. Observations provided by mesoscale observing networks, in certain coastal or interior regions of continents, will be used when available to validate forecasts at smaller than synoptic-scale. Forecast improvement will be evaluated using deterministic and ensemble forecast systems, and through assessments performed in societal and economic impact studies.

2. Research Proposal

The objectives of THOR*pex* will be addressed through four sub-programs: i) Predictability Research and Numerical Experimentation (Section 2.1); ii) The Observing System: demonstration and field-test evaluation (Section 2.2); iii) The Hemispheric Field Campaign (Section 2.3); iv) Societal and Economic Impact Assessment (Section 2.4).

2.1 Predictability Research and Numerical Experimentation

THOR*pex* will carry out studies of predictability and dynamical processes to determine which spatial and temporal scales of motion must be better observed, analyzed, parameterized, and simulated for the improvement of short and medium-range forecasts.

Concurrent research and numerical experimentation with real and idealized observations will be used to develop strategies for the design and deployment of new observing systems, and to optimize and improve methods for the assimilation of observations. The primary predictability and numerical experimentation objectives are summarized below under the headings (a) Predictability and Dynamical Process Research and (b) Data Assimilation and Observing System Experiments. A set of preliminary THOR*pex* research objectives prepared by various forecast centers and research agencies is available on-line, via web-page links provided in Section 3.

a) Predictability and Dynamical Process Research

- Identify those flow regimes within which high-impact weather events are inherently more difficult to predict. These regimes may occur on periods of days or weeks (e.g, blocking or blocking transition), or on seasonal and inter-annual cycles (e.g., ENSO, and North-Atlantic Oscillation). Perform diagnostic studies of analyses and forecasts of the life-cycles of high-impact weather systems.

- Determine the relative importance of model error and initial condition error in the growth of forecast errors at various lead times. This includes the effect of upscale energy transfer from poorly-resolved and parameterized scales on the predictability of the resolved systems.

- Assess weaknesses in model parameterizations of subgrid-scale physical processes and contribute to the development of improvements to those parameterizations.

- Develop climatologies of inter-annual and intra-seasonal variations in forecast error sensitivity and associated flow regimes. Assess the use of stochastic climate forecasts to plan, several months in advance, for deployments of additional observing resources in particular regions.

- Assess the influence of organized intra-seasonal tropical convection (including Madden-Julian Oscillations and east Pacific equatorial convective flare-ups) and the effects of tropical-extratropical teleconnections on the predictability of medium-range forecasts.

- Diagnose the dynamical processes through which errors on various scales amplify and propagate (e.g., energy conversions, Rossby-wave dispersion and instability mechanisms). For example, Fig. 4 illustrates the effects of a downstream amplifying Rossby-wave packet in the development of the poorly-predicted 25 January 2000 U.S. East Coast snowstorm.

b) Data Assimilation and Observing System Experiments

- Conduct Observing System Simulation Experiments (OSSEs) with "virtual" data and Observing System Experiments (OSEs), using archived data from winter storm field programs (e.g., FASTEX, NORPEX, WSR) to determine: i) optimal sampling patterns for satellite and *in-situ* observations; ii) potential forecast impact of new observing systems; iii) requirements for observations in terms of horizontal, vertical and temporal resolution, and accuracy of key variables.

- Develop targeted observing methods that incorporate dynamical information and properties of the data assimilation system, including adjoints of data assimilation procedures and ensemble-based Kalman Filters. New methods are needed for targeting in medium and extended-range forecasts. Here, "targeting" is broadly defined to include the addition of observations in certain regions at certain times, or intensive sampling of a region for periods of several days or weeks, e.g., flow regime targeting.

- Identify critical gaps in the global observing network. Gaps in observing coverage may refer to limitations such as the lack of cloud-track wind observations in high latitudes, density of the operational radiosonde network, sparsity of satellite data below upper cloud layers, or other factors.

- Contribute to the development and testing of advanced data assimilation techniques for the improved use of existing satellite and *in-situ* data over oceanic and arctic regions, including improved covariance estimation, 4d-Var development, ensemble Kalman filters, moisture assimilation, and advanced procedures for assimilation of targeted data.

2.2 The Observing System: development and field-test evaluation

A central aspect of THOR*pex* is to improve the use of existing *in-situ* and space-based observations. In addition, THOR*pex* will develop and evaluate new observing technology designed to improve the observational quality and coverage in critical regions of the atmosphere. This section describes both existing observing systems, and those under development, that will contribute to the THOR*pex* database. The observing system field-test and evaluation will be accomplished during a series of regional field experiments designed to address specific predictability issues. The regional experiments will provide data sets to test observing strategies, data assimilation, and predictability hypotheses in particular geographic areas of the northern hemisphere. Observing system components and experiments are discussed below under the headings: a) Satellite Observing Systems, b) *In-Situ* Observing Systems, and c) Regional Field Experiments.

a) Satellite Observing Systems

The current meteorological satellite observing system is comprised of a constellation of geosynchronous and polar-orbiting satellites operated by national or conglomerate space agencies. Each satellite carries at least a multispectral imaging radiometer. Satellite observations have become an integral part of our weather forecast system, and if fully exploited, will offer even greater contributions to an optimal global observing network. Advancements in improved microwave sensors and hyperspectral imaging and profiling will provide new opportunities and challenges. Additional information about satellite plans and capabilities in contained in Appendix A.

THOR*pex* will not influence the design of weather satellite sensors deployed over the next decade. However, THOR*pex* research and its field programs will provide validation datasets to accurately assess satellite data impacts, and will influence decisions regarding observational requirements for future satellites. THOR*pex* will demonstrate optimal sampling rates and spatial/spectral filtering of satellite data by targeting specialized observations (such as rapid scan wind products) into certain regions, and by processing in an adaptive sense the large (and potentially overwhelming) amount of data expected from new satellite hyperspectral sounders. The development of methods to extract the maximum information content from satellite observations will be a THOR*pex* research priority.

b) In-Situ Observing Systems

THOR*pex* will evaluate and test a variety of *in-situ* observing systems (see Appendix B) that provide upper-air or surface observations where supplemental data are needed to complement existing satellite data. We anticipate that these *in-situ* observations will significantly improve analyses in cloudy regions, and also increase the information extracted from satellite data outside the cloudy regions by improving the background fields used by data assimilation. If verified, these results would provide evidence to support the development of future satellite sensors (e.g., active microwave sounders) for improved observations in cloudy regions. These issues present research challenges for THOR*pex*, and opportunities to test new observing system and data assimilation approaches. The test and assessment results, together with the research outlined in Section 2.1, will determine which *in-situ* observing systems are used to supplement satellite observing systems during the Regional Experiments and Hemispheric Field Campaign of THOR*pex*.

c) Regional Field Experiments

Regional field experiments will be conducted in advance of the THOR*pex* Hemispheric Campaign to test observing and forecast systems in conditions leading to high-impact weather. These experiments will address specific regional predictability questions on the 0-5 day time scale and provide test-beds for new observing systems, assimilation schemes and targeting methodologies. Co-ordination of the regional field experiments will reside with three sub-committees of the THOR*pex* Scientific Steering Committee. The proposed Regional Field Experiments are:

One **European** North Atlantic Experiment will take place in October to November, when cyclones that have undergone tropical to extratropical transformation have historically been characterized by low predictability and high societal/economic impact. A second experiment would take place in January to March when smaller, rapidly developing cyclones develop in the mid Atlantic storm-track and affect north-west Europe. Polar lows and Greenland vortices develop in regions with lower density of conventional observations and subsequently impact northern European weather. On the medium-range, there is a known sensitivity of European forecasts to perturbations over the Canadian Arctic.

The **North-American** Experiment will be conducted in mid-winter during the period of highest vulnerability to east and west coast cyclones and mid-continent Canadian arctic outbreaks and blizzard conditions. This range of forecast problems will require experiments both over the Pacific storm-track as well as over North America. The timing of these experiments will be influenced by the sensitivity of north-American high-impact weather to the phase of ENSO and its intra-seasonal variability.

One **Asian** Experiment will take place during late spring and/or summer to test the regional impact of THOR*pex* experimental observing systems, data assimilation methods, and model paramterization improvements, including the use of coupled atmosphere-ocean models, on forecasts of land-falling tropical cyclones, and extreme precipitation events along the Meiyu front. In addition, this region is one favored for the convective initiation of the Madden-Julian Oscillation which is known to impact mid and high-latitude weather throughout both hemispheres. A second experiment will take place during the cool season, when cold-air outbreaks occur.

2.3 The Hemispheric Field Campaign

The Hemispheric Campaign is the ambitious concept at the heart of THOR*pex*. It aims to integrate new and existing observing and forecast systems in order to test the predictability and assimilation advances made from the THOR*pex* research and regional field experiments. It will demonstrate the potential for improved operational forecasts on all predictable spatial scales, and time-scales out to 10 days using enhancements to the global observing system. Through this accomplishment, THOR*pex* will provide guidance to national weather services and agencies in their ongoing mission for permanent enhancements to the observing system and improved forecasts of high-impact weather. The THOR*pex* data-set will be an invaluable resource for agency and university research.

The THOR*pex* Hemispheric Campaign will deploy the full complement of experimental and operational observing systems. This will include *in-situ* systems (driftsonde, UAVs, rocket-buoy, and other platforms described in Appendix B), spatial and temporal enhancements of data provided by satellite systems described in Appendix A, and operational radiosonde and bi-directional RAOB soundings targeted at 6-hourly intervals over sections of Russia, North America, and Asia. Data collected in THOR*pex* will be available in near real-time and archived by NCAR/JOSS, and at operational forecast centers.

Figure 5 is a conceptualization of how one of the candidate *in-situ* observing systems (driftsonde) could be used in the THOR*pex* Hemispheric Campaign to provide large numbers (~100 per day) of high-quality upper-air soundings over the North Pacific Ocean. Each solid dot in Fig. 5 represents the location of a GPS dropsonde profile and an individual driftsonde carrier balloon/gondola platform from which the dropsonde is deployed. In this example, the carrier balloons are launched every 12 hr from four sites in Japan, and each carrier balloon can deploy up to 24 dropsondes at 6-hr intervals. The trajectories for this example are based on time-averaged 100-mb winds for January and February 1999, and the driftsonde carrier balloons reach the west coast of North America after ~72 hr. The deployment of driftsondes and other *in-situ* observing systems during the Hemispheric Campaign will be carefully coordinated to provide the best possible data set for operations and research.

The Hemispheric Campaign will occur over at least one season, but preferably extend up to one year. It is an intensive effort to obtain a comprehensive observational data set encompassing the entire Pacific and Atlantic Ocean basins and large sections of the Arctic. The timing of the Hemispheric Campaign will be dictated in part by the deployment of certain critical satellite observing systems (e.g. GIFTS or COSMIC). An observing system upgrade of this geographic scope and duration has not been previously attempted in any program. The Hemispheric Campaign therefore has the potential to demonstrate unprecedented gains in forecast skill of high-impact weather over large areas of the Northern Hemisphere. THOR*pex* continues and extends the visionary thinking represented in the First GARP Global Experiment, FGGE (Gosset 1979).

2.4 Societal and Economic Impact Assessment

The societal and economic impact component will assess the costs and benefits of implementing THOR*pex* research results into operational practice. This assessment will be made available to operational and research agencies that make decisions on the future allocation of finite resources to the various components of civilian and military weather services. The assessment of costs and benefits associated with the production and use of weather information is a complex interdisciplinary issue. THOR*pex* societal impact studies will integrate the meteorological operations and research elements with broader societal concerns through the following three research components:

a) Assessment of High-Impact Weather and Forecasts

This component of THOR*pex* societal impact research will assess the economic and other human consequences of high-impact weather and forecasts. The assessment will quantify the costs and effects of high impact weather, providing a baseline to quantify the actual and potential value of forecasts and forecast improvements. It will also help to identify potential users of forecast improvements in the weather-sensitive commercial sector. In addition, forecast parameters that the assessment finds to have significant impact may be incorporated into verification measures as discussed in sub-section 2.4c, below.

b) Use and Value of Forecast Information

THOR*pex* researchers will evaluate the use and value of current and improved forecasts by performing case studies for various public and private users. Each case study will examine the decisions that a user or class of users makes with weather information. The decision models describe how the users incorporate forecast information, and can take a number of forms, including a verbal description, an equation, a computer simulation, a flow chart, or another type of diagram.

Each case study will evaluate the user's success with respect to their goals. A norm related to the forecast parameters in the user's decision model will be used to assess the quality of both current forecasts, and those produced with improved observing and forecast systems. Improved forecasts can be simulated using archived forecasts, "virtual data", or evaluated from field tests of THOR*pex* observations. The results will be available to governments and international agencies for guidance on the future allocation of resources for improved weather services.

The primary goal of the case studies is to document the potential value of improved forecast information to weather-sensitive public and private-sector users. While working with users or forecasters, developing or running a decision model, or estimating the value of different forecasts, researchers may discover barriers that prevent society from obtaining the maximum benefit from current or future forecasts. In addition to estimating value, therefore, some of the case studies may describe such barriers and, where appropriate, identify methods to eliminate them. These methods might include the use of forecast parameters that can be derived from the primary output of numerical models but have not traditionally been available. The parameters would then be candidates for developing verification measures, as in sub-section 2.4c, below.

c) Development of Verification Measures

The statistical metrics used by operational forecast centers to evaluate forecast skill are, in many cases, not directly relevant to those public or private end-users who use weather forecasts to make decisions. For example, norms such as the anomaly correlation are often used to evaluate model skill, but have little or no direct meaning to many potential forecast information users, such as utility companies or highway departments. THOR*pex* will therefore quantify forecast improvements using a wide range of parameters, including those identified in sub-sections 2.4a and 2.4b, above.

For some forecast parameters, verification measures may be already established or simple to develop; for example, an energy company might be interested in the distribution of errors in heating degree days, or in one or more statistics that summarize the error distribution. For other parameters, such as precipitation, researchers may need to develop modified or new verification measures that are relevant to one or more users, yet are efficient, reliable, and possess other desirable characteristics discussed in Murphy (1997).

In some cases, the forecast end-user may rely on products developed by numerical or statistical post-processing of the primary forecast fields provided by the models. The NWS, for example, is in the process of developing a system to provide temperature, rainfall and other information derived from model output statistics to the public on a high-resolution (~ 3 km) grid. In this context, the assessment of forecast improvement may be quite different from that provided by traditional model skill scores.

The concept of “end-to-end” forecasting (Smith et al. 2001) considers the direct prediction of economic variables that have a weather dependent component. Its goal is to translate uncertainty in the weather into uncertainty in the quantity of interest to the user (e.g., energy demand). Previous work in the field has considered rather simple cases of forecasting to make binary choices (for example, whether or not to salt an icy road) using cost-loss analysis. However, new techniques are developed for economic situations where the outcome is a continuous variable (e.g., demand) and where the decision is also a continuous variable (e.g., production). Smith et al. (2001) show how probabilistic forecasts of demand can be used to make production decisions and produce probability density functions for the profit of a given business activity. These and other new techniques for assessing the societal and economic benefit of weather forecasts will be used and developed as part of THOR*pex*.

3. Scientific Management

A comprehensive THOR*pex* Science Plan will detail numerical and theoretical studies of observing network design, targeting procedures, and plans for use of satellite and *in-situ* observations. It will be prepared by a International Science Steering Committee (SSC) to be formed in 2002. The SSC will include specialists in data assimilation, observing systems, numerical modeling, predictability, phenomenology, atmospheric dynamics, and forecast product end-users from government and industry. THOR*pex* program management will be conducted by a Core Steering Group (CSG) to be formed in 2002 that represents the principle international sponsoring agencies.

Agency Research Objectives (in alphabetical order)

European Center for Medium-Range Weather Forecasts
Japan Meteorological Agency
Meteo France
Meteorological Service of Canada
NASA Data Assimilation Office
NASA GIFTS Project
NOAA Climate Diagnostics Center
NOAA Environmental Technology Laboratory
NOAA National Centers for Environmental Prediction
Roshydromet

The European Composite Observing System

U.K. Met Office

U.S. Joint Center for Satellite Data Assimilation

U.S. Naval Research Laboratory

Observing System Web Sites

Aerosonde Web Site (Australian Group)

The Insitu Group (Aerosonde) Web Site

Weather Rocket-Buoy Web Site

Observing System Proposals and Articles

Boeing Scan Eagle UAV

Driftsonde Powerpoint Presentation (pdf format)

Aerosonde Paper 1

Aerosonde Paper 2

Bi-Directional RAOB

GAINS

"Smart" Balloon

Stratospheric Satellites

Acronyms

AIRS	Atmospheric Infrared Sounder (NASA)
AL	Aeronomy Laboratory (NOAA)
AMDAR	Aircraft Meteorological Data Reporting
AMSU	Advanced Microwave Sounder
ATD	Atmospheric Technology Division (NCAR)
CBS	Commission on Basic Systems (WMO)

CDC	Climate Diagnostics Center (NOAA)
CGC	Co-ordination Group for the Composite Observing System for the North Atlantic (WMO)
CIMSS	Cooperative Institute for Meteorological Satellite Studies (Univ. of Wisconsin – Madison)
CLIVAR	Climate Variability and Predictability
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CWRP	Canadian Weather Research Program
DAO	Data Assimilation Office (NASA)
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center (NOAA)
ENSO	El Niño – Southern Oscillation
ESA	European Space Agency
ESIG	Environmental and Societal Impacts Group (NCAR)
ETL	Environmental Technology Laboratory (NOAA)
ET-RR	The WMO/CBS Expert Team on Observational Data Requirements and Redesign of the Global Observing System
EUCOS	The European Composite Observing System
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FASTEX	Fronts and Atlantic Storm-Track Experiment
FGGE	First GARP Global Experiment
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FSL	Forecast Systems Laboratory (NOAA)
GARP	Global Atmospheric Research Program
GIFTS	Geostationary Imaging Fourier Transform Spectrometer (NASA)
GMS	Geostationary Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite

GPS	Global Positioning System
GSFC	Goddard Space Flight Center (NASA)
GTS	Global Telecommunication System
JMA	Japan Meteorological Agency
JOSS	Joint Office for Science Support (UCAR)
JPL	Jet Propulsion Laboratory (NASA)
LaRC	Langley Research Center (NASA)
LEO	Low-Earth-Orbiting Satellite
MMM	Mesoscale and Microscale Meteorology Division (NCAR)
MSFC	Marshall Space Flight Center (NASA)
NAOS	The North American Atmospheric Observing System
NASA	National Aeronautic and Space Administration
NAST-I	NPOESS Atmospheric Sounder Testbed-Infrared
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction (NOAA)
NESDIS	NOAA Environmental Satellite Data and Information Service
NOAA	National Oceanic and Atmospheric Administration
NORPEX	North Pacific Experiment
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NSF	National Science Foundation
NRL	Naval Research Laboratory
NWS	U.S. National Weather Service
ONR	Office of Naval Research
PACJET	Pacific Landfalling Jets Experiment (ETL)
PMEL	Pacific Marine Environmental Laboratory (NOAA)
SSMIS	Special Sensor Microwave Imager/Sounder
SUNY	State University of New York
TAMEX	Taiwan Area Mesoscale Experiment
TAO	Tropical Atmosphere Ocean Project
THOR*pex*	The Observing System Research and Predictability Experiment
UAV	Unmanned Aerial Vehicle

UCAR	University Corporation for Atmospheric Research
UKMO	United Kingdom Meteorological Office
USAF	United States Air Force
USWRP	U.S. Weather Research Program
WGNE	Working Group on Numerical Experimentation (WMO)
WMO	World Meteorological Organization
WSR	Winter Storm Reconnaissance (NOAA)
WWRP	World Weather Research Program (WMO)

Contributors:

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21 September 2001

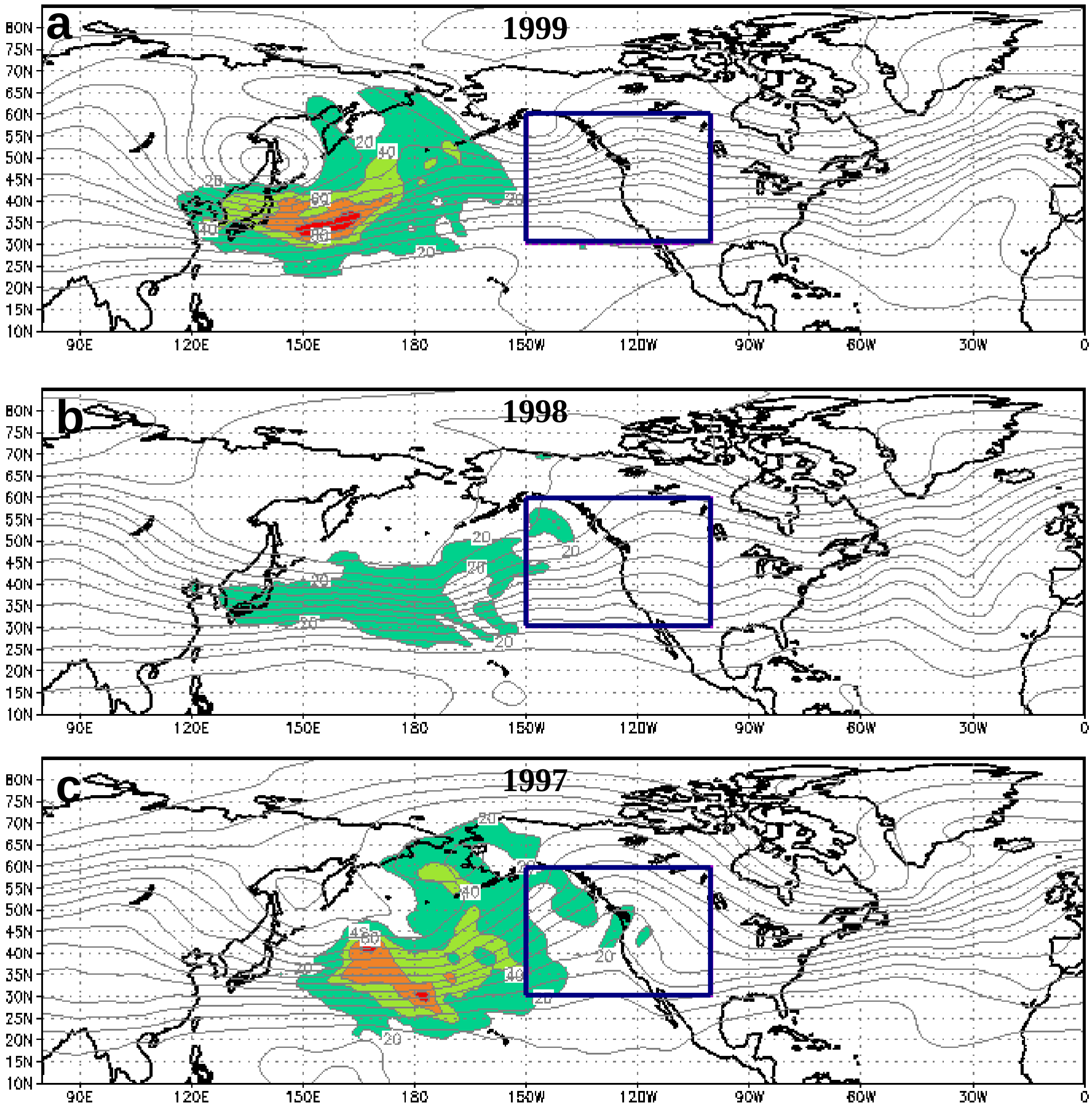


Fig. 1: Initial condition sensitivity for 72-hr forecast cases with the largest errors during January and February. Forecast errors verify in the area 30N-60N, 100W-150W. Average sensitivity in the nine worst forecast cases is shown for each year. The sensitivity combines wind, temperature and pressure from the surface to 150mb, and is computed with the adjoint of the Navy global model (NOGAPS). Sensitivity units are J kg^{-1}. The average of analyzed 500mb height for the nine cases in each year is shown as solid light contours (interval = 60m).

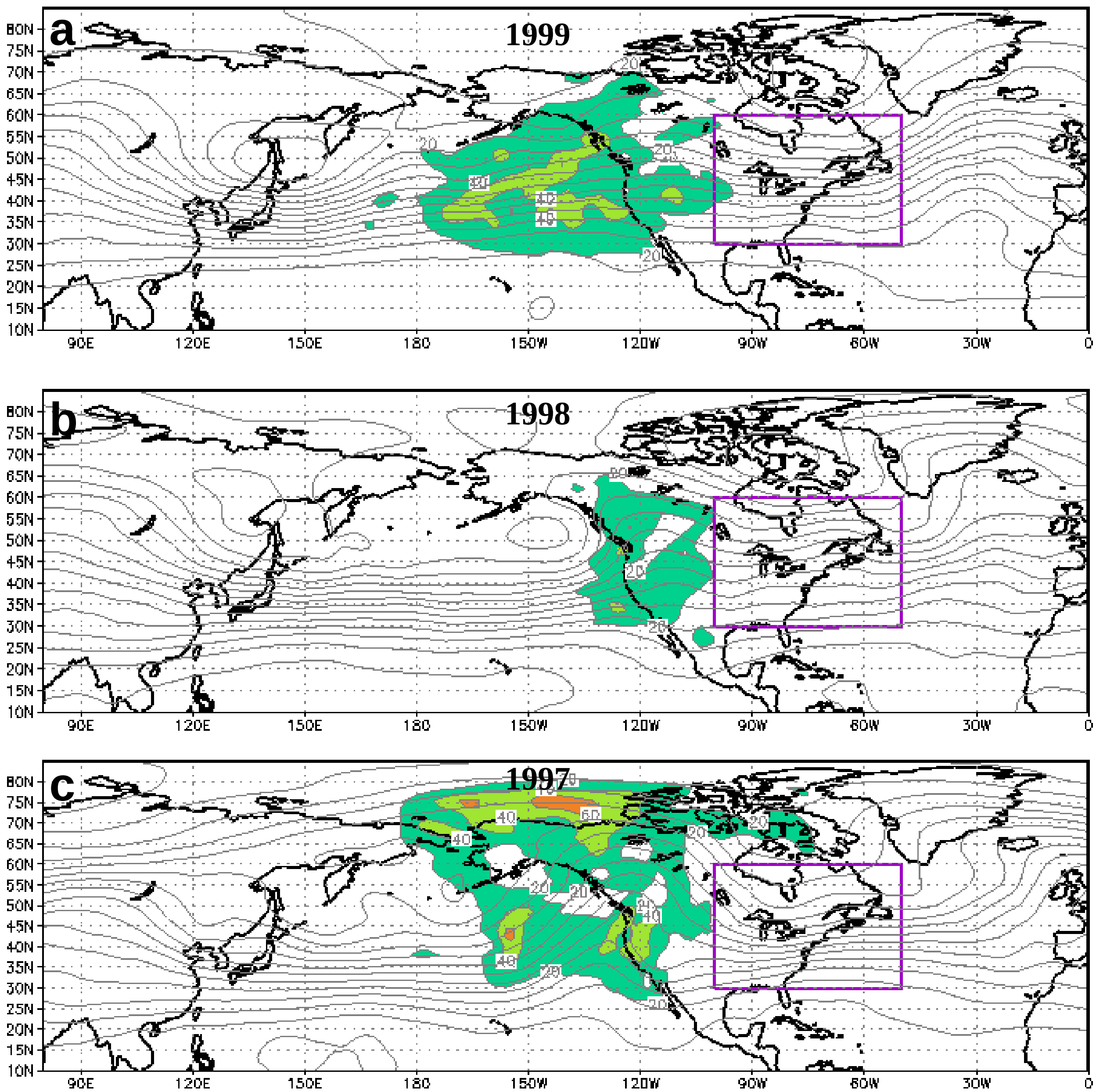


Fig. 2: Initial condition sensitivity for 72-hr forecast cases with the largest errors during January and February. Forecast errors verify in the area 30N-60N, 50W-100W. Average sensitivity in the nine worst forecast cases is shown for each year. The sensitivity combines wind, temperature and pressure from the surface to 150mb, and is computed with the adjoint of the Navy global model (NOGAPS). Sensitivity units are J kg^{-1}. The average of analyzed 500mb height for the nine cases in each year is shown as solid light contours (interval = 60m).

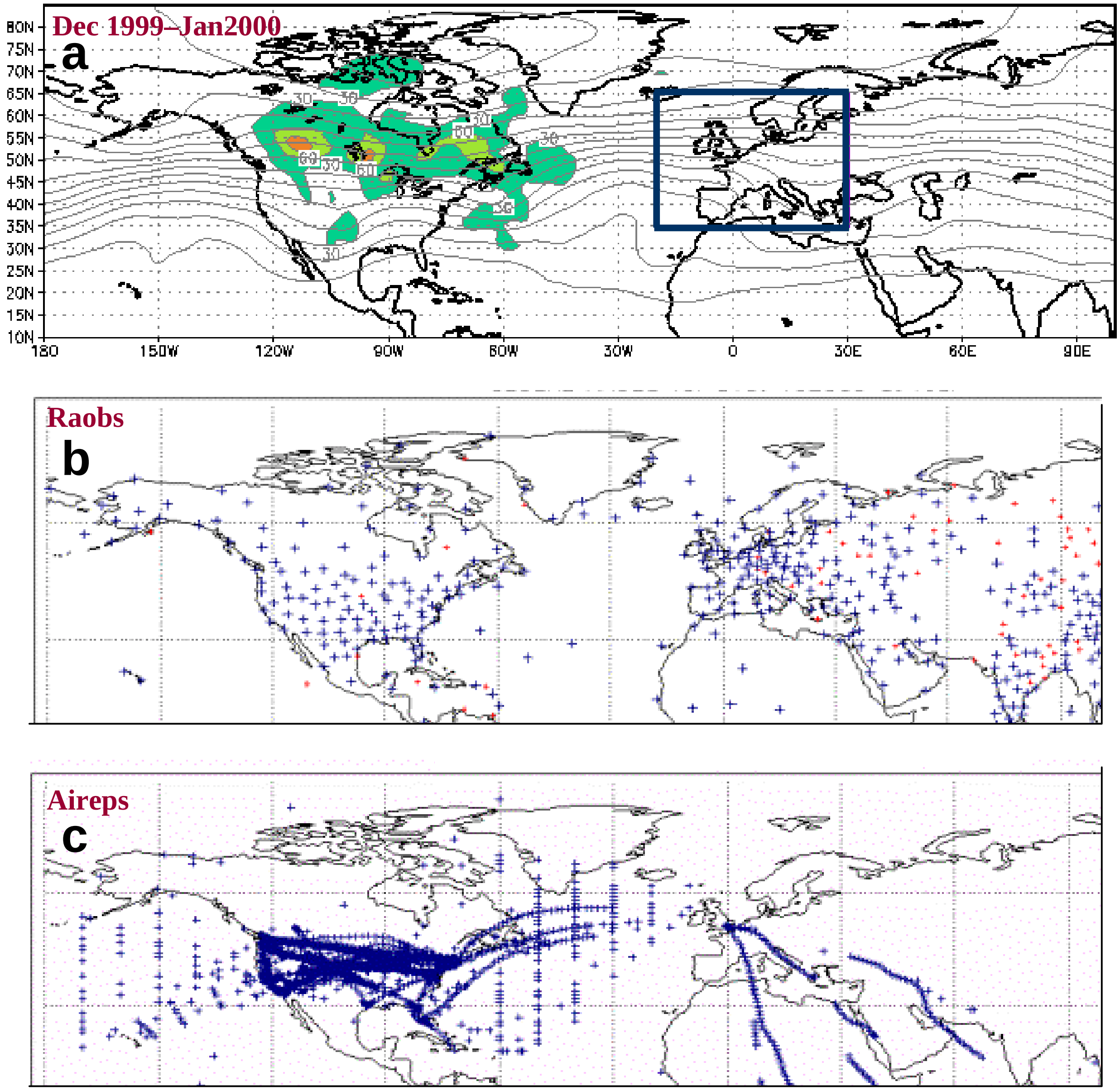


Fig. 3: Top panel is initial condition sensitivity (defined as in Figs. 1,2), except for 96-hr forecast cases with the largest errors during December 1999 and January 2000 that verify in the area 35N-65N, 20W-30E. Center and lower panels are observational coverage provided operationally by radiosondes and aircraft data, respectively at 00UTC 20 October 1999.

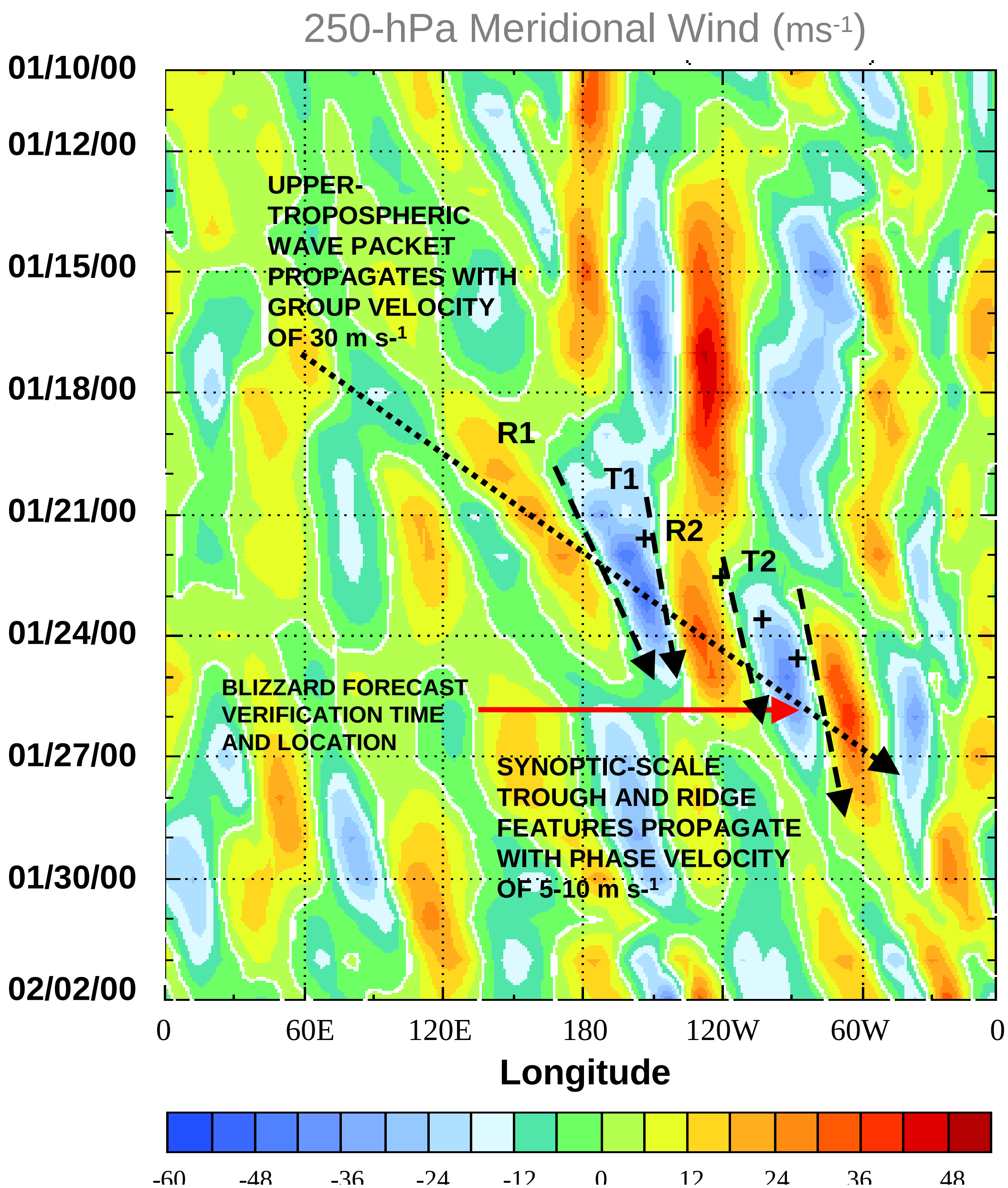
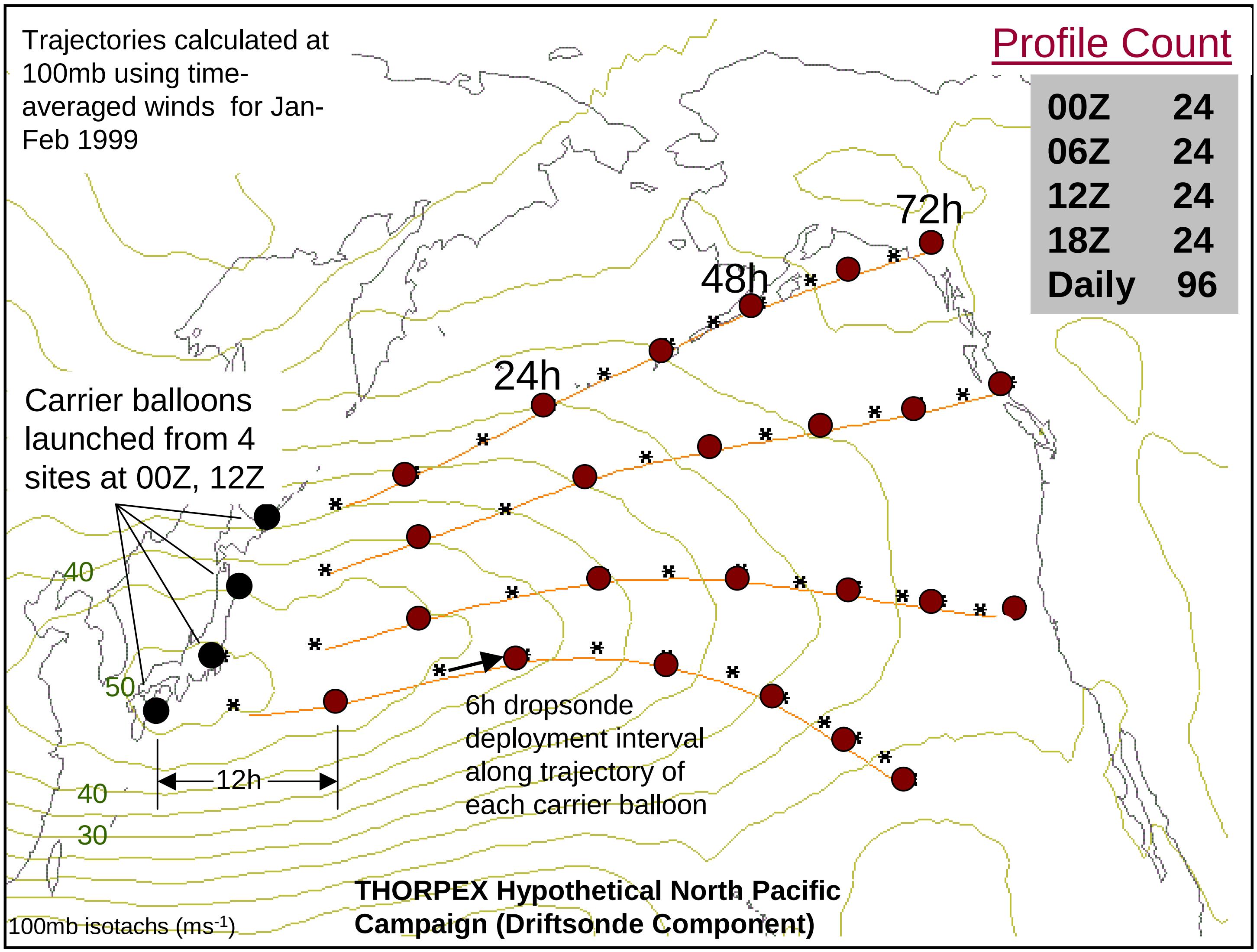


Fig. 4: Forecast errors propagate at group velocity of the wave packet in which they are embedded, with profound implications for predictability. Sensitivity of forecast error (crosses) also follows the group velocity. The Washington, D.C. major snowstorm of 25 January 2000 (red arrow) was part of a wave packet that traveled from the mid Pacific to the US east coast in 72 hours. Accurate analysis of this group in the Pacific would have been necessary for accurate 72-hour forecasts of the storm.

Adapted from Langland et al. (2001). Image provided by the NOAA-CIRES/Climate Diagnostics Center, Boulder, Colorado from their web site at www.cdc.noaa.gov.

Fig. 5: Driftsonde profile coverage at one assimilation time, after 3 days of deployment from 4 launch sites in Japan – each dot represents a separate carrier balloon / gondola and GPS dropsonde profile location at 00Z (or 12Z) - stars are profile locations at 06Z or 18Z



THOR*pex*

Appendix A: Satellite Observing Systems

A.1 Geosynchronous Satellites

The period 2001-2005 will witness an upgrade in the capabilities of global geosynchronous satellites. The Meteosat (Europe) and GMS (Japan) series will be replaced by next generation versions (Meteosat Second Generation and MTSAT, respectively). The INSAT (India) program is beginning to employ advanced technologies. The GOMS (USSR) and FY (China) series are expected to mature during this period. The GOES (USA) program is expected to continue a two-satellite operation. The primary variables that can be derived from these satellites include temperatures (radiances), moisture and winds. The major advantage of geo-sensing is the time-continuous sampling over large areas of the globe. Rapid-scan operations over focussed or targeted regions are also possible. The disadvantage is the lack of microwave frequencies to complement the IR spectrum, leading to observation voids in and below clouds.

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) represents a revolutionary step in geo-satellite based remote sensing. It is part of NASA's New Millennium Program - Earth Observing System (EOS) mission. Following the expected launch in 2005, GIFTS will be positioned over or near the continental United States and adjacent oceans for 12 to 18 months. NOAA will help evaluate GIFTS during this period. It will then be positioned over the Indian Ocean for a 5-year period to support U.S. Navy operations. The goal of the measurement concept validation activities during the year following launch is an assessment of the accuracies of the core GIFTS products for a representative set of observation conditions. Of particular interest is the validation of the navigated and calibrated high-spectral- resolution radiances, temperature and water-vapor profile retrievals, wind retrievals, carbon monoxide and ozone concentration retrievals, cloud-property retrievals, and data compression. In this context THOR*pex* can play a key role by providing validation measurements through field campaigns (e.g., high spatial-resolution soundings from the NOAA G-IV reconnaissance aircraft), and further assessment of the importance of GIFTS observations through post-analysis and forecast impact studies.

A.2 Polar-Orbiting Satellites

A number of advanced polar-orbiting satellite systems are expected to be operational or experimental during 2001-2005. These systems will employ multi-frequency microwave radiometers capable of penetrating clouds and detecting precipitation rates. Radiances from the NOAA satellites have been shown to have a positive impact on NWP. The disadvantages of the polar orbiters are the less frequent sampling and limited swath coverage.

A new generation of operational atmospheric monitors, The Atmospheric Infrafred Sounder (AIRS), the Advanced Microwave Sounder (AMSU) and the Humidity Sounder Brazil (HSB) are scheduled to fly together on the second platform of NASA's Earth Observing System (EOS AQUA), in 2002. AIRS is a high spectral resolution spectrometer with coverage in nearly 2400 bands in the infrared and visible ranges: 3.7 - 15 microns (10^{-6} m) and 0.4 - 1.0 microns. AIRS obtains temperature and moisture profiles by observing the "signature" of carbon dioxide near the wavelengths of 4.2 µm and 15 µm and water vapor near 6.3 µm. By observing at very high spectral resolution (very narrow bands) at several wavelengths near the central absorption feature (4.2, 15, or 6.3 µm, for example), one "sees" to different levels in the atmosphere. The strength of the signal at a specific band is also dependent on temperature. To determine the temperature or humidity at a specific altitude (or pressure), AIRS takes the signals from many different spectrally narrow bands, assigns pre-determined weighting functions to each band based on previous observations, and uses them to derive a vertical profile that fits the signals.

The Global Positioning System (GPS) offers a promising new technique for measuring temperature, pressure and water vapor. It employs the radio occultation technique, which was developed by scientists at Stanford University and the Jet Propulsion Laboratory (JPL) for the remote sensing of planetary atmospheres. The relevance of this technique for accurate sounding of the Earth's atmosphere was demonstrated by the GPS/MET (GPS/Meteorology) program. GPS/MET demonstrated atmospheric limb sounding from low-earth-orbit (LEO). Based on the success and scientific results of GPS/MET, a consortium of international agencies are developing COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate), a follow-on project for weather and climate research, climate monitoring, space weather, and geodetic science. COSMIC plans to launch six LEO (low-Earth orbiting) satellites in 2005. Each COSMIC satellite will retrieve about 500 daily profiles of atmospheric thermodynamic properties from the tracked GPS radio-signals as they are occulted behind the Earth limb. COSMIC data will be available for testing in real-time in operational NWP models. The data will be assimilated into the models using three-dimensional or four-dimensional variational techniques. Either of these data assimilation techniques may assimilate bending angles, refractivities, or derived temperature and water vapor data.

Note: Additional Information about satellite system capabilities is contained in an extract from Annex A of the WMO SAT-26, Technical Document 1052.

THOR*pex*

Appendix B: In-Situ Observing Systems

B.1 Commercial Aircraft

Commercial airlines are providing increased amounts of flight-level temperature and wind observations and ascent and descent profiles that are assimilated at operational forecast centers. The value of these aircraft data (AMDAR) in improving forecasts has been demonstrated (Graham et al. 2000). The greatest density of observations is currently provided over North America and Europe, although some data are also provided in trans-Pacific and trans-Atlantic flights, and in other parts of the world. Russia is seeking to add more AMDAR over its territory and in polar regions. It is essential that THOR*pex* consider the benefit that can be obtained from AMDAR and other aircraft observations. There are also ongoing efforts to develop the capability to deploy dropsonde capability and Doppler lidar on some commercial aircraft.

B.2 Automated Shipboard Soundings

The Automated Shipboard Aerological Program (ASAP) currently provides a small number of upper-air soundings (~ 20 daily) from commercial and military ships of opportunity. The potential to increase the number and frequency of ship soundings is currently being investigated as part of EUCOS and will also be considered in THOR*pex*.

B.3 Reconnaissance Aircraft Soundings

Upper air soundings from GPS dropsondes deployed by manned reconnaissance aircraft (NOAA G-IV and USAF C-130s) have been the primary source of targeted data in FASTEX, NORPEX, and WSR. The WSR will continue to provide targeted dropsonde data (several hundred soundings per winter) over the northeast Pacific during January to March, and there is the option of extending these operations to the northwest Pacific as part of THOR*pex*. Work is also underway at NOAA/ETL to develop lidar wind and aerosol lidar sounding systems for deployment on C-130 aircraft. These systems could potentially be deployed during THOR*pex*.

A multiband airborne imaging system based on the NOAA Polarimetric Scanning Radiometer (PSR) will provide measurements of rain rate, temperature and water vapor profiles, ocean surface wind fields, and cloud water and ice content. This system is being developed at NOAA/ETL for operation on the WB-57F aircraft. Plans for the system include both passive microwave radiometers and a Ku-band cloud radar to provide comprehensive characterization of the atmosphere over a swath of ~50 km width and a track of ~2500 nm length. The spatial resolution of ~1-3 km will permit unambiguous sampling of cloud and storm front features, and the use of microwaves will permit observations through stratus decks. A dropsonde system is also to be included. The contributions of this data will include spatial interpolation between dropsonde profiles and precise identification of convective regions and water vapor bands. The WB-57F platform would be configured to host several additional remote sensing instruments, including wind and cloud lidars. A transition pathway from the WB-57F to the use of commercial Canberra aircraft also exists to provide extended observational support for THOR*pex*.

B.4 Driftsonde

The driftsonde is a new cost-effective observing system that will produce frequent (6-hr) coverage over wide oceanic, remote arctic and continental regions with large numbers (~100-day or more) of high-vertical-resolution GPS dropsonde profiles through the lower stratosphere and entire troposphere. The soundings can be obtained at specified times and are not affected by cloud-cover or icing conditions. A network of driftsondes will be able to provide simultaneous profiles (for example, at 6-hr assimilation times) over large expanses of data-sparse regions, which cannot be accomplished with the limited number of weather reconnaissance aircraft that are available for conventional dropsonde deployment. The driftsonde can be considered an “adaptive” observing platform, since it can be deployed into specific regions when needed.

The driftsonde observing system includes a polyethylene balloon with an attached gondola that carries a payload of up to 24 GPS dropsondes. The carrier balloon ascends to between 50 and 100 mb, like a conventional radiosonde, and then drifts in the prevailing stratospheric westerlies for up to five days, deploying dropsondes at prescribed intervals over data-sparse regions of interest. Data is transmitted from each dropsonde and sent via a low-earth-orbiting satellite (LEO) to the ground station for transmission to the GTS in real-time. The gondola will also measure pressure, temperature, humidity and balloon position and velocity every hour and send that data through the satellite. Current plans call for a series of in-field driftsonde tests to be conducted by NCAR/ATD starting in late 2001.

Driftsonde Powerpoint Presentation (pdf format)

B.5 Aerosonde (Unmanned Aerial Vehicle)

The aerosonde is a remotely-controlled miniature aircraft that provides flight-level measurements of temperature, wind, humidity and pressure. With careful route planning and choice of launch and recovery sites, much of the North Pacific and North Atlantic oceans will be accessible for aerosonde or other UAV reconnaissance. The present state-of-the-art aerosonde has a range of approximately 5,000 km and maximum altitude of 7 km, although routine operations will normally be restricted below 5-6 km. It is possible to obtain vertical "soundings" in specific locations by flying the aerosonde between its maximum altitude and a level near the ocean surface. Icing is a potential limiting factor for aerosonde operations in certain regions. Aerosonde capability is currently being developed by Aerosonde Robotic Aircraft and the Insitu Group. UAV tests are on-going in various locations, and a trans-Pacific flight (Japan to Canada) has been proposed for late 2001 or early 2002

Aerosonde Web Site (Australian Group)

The Insitu Group (Aerosonde) Web Site

At ETL, experience gained in using the WB-57F and related airborne systems is being applied to the development and deployment of a permanently-flying UAV supporting several passive microwave and active optical sensors. This platform, based on the solar-powered Helios vehicle, will greatly expand the ability to provide airborne in-situ observations by eliminating range and refueling restrictions, operating for up to months continuously. A sensor pod is currently under development at NOAA/ETL. Operational useage within tropical to midlatitude regions for Thorpex could be expected as early as mid-2004.

B.6 Weather Rocket-Buoy

The weather rocket-buoy is designed to provide high-quality upper-air observations over deep mid-tropospheric regions in all weather conditions, including icing, and regardless of sea-state, from a synoptic network of anchored buoy platforms deployed over wide oceanic regions. The buoys, designed for heavy seas, will hold a 1-year supply (one or two soundings per day) of rocketsondes, sealed in separate launch tubes. The rocket will ascend to ~8 km, and deploy a GPS dropsonde that transmits observations of temperature, wind, pressure, and humidity as it falls back to the surface. The system may also be used to obtain soundings as an unmanned land-based system in remote arctic regions. The weather-rocket buoy is being developed at the University of British Columbia in collaboration with NOAA and Vaisala.
Weather Rocket-Buoy Web Site

B.7 Stratospheric Balloon Systems

StratCon is a constellation of hundreds of stratospheric superpressure balloons, called StratoSat™ platforms that could simultaneously provide hundreds of targeted high-resolution GPS dropsonde profiles through the stratosphere and troposphere. StratCon is being developed for NASA as a revolutionary, low-cost, and adaptive observing system that could provide global or regional Earth observations or targeted coverage in data sensitive areas. In addition, StratCon could provide continuous remote sensing and *in situ* measurements with a suite of instruments including high resolution Wind Lidar, Precipitation Radar, Radiometers, and Visible and IR Cameras. StratoSat™ platforms float in the stratospheric winds at 35-km altitude, fly for up to 10 years after launch, have some maneuvering capabilities and can perform a multitude of tasks. StratoSat™ platforms can carry a payload of at least 250 kg using a smaller and advanced version of the NASA Ultra Long Duration Balloon (ULDB). StratoSat™ platforms are guided by a Trajectory Control System (TCS) that is a suspended vertical wing that uses the natural difference in wind speed and direction at different altitudes in the atmosphere to drag the balloon across the relative wind. The TCS enables individual balloons to be maneuvered and a network of StratoSat™ platforms to be configured for high frequency observations over specific target areas, such as hurricane tracks or regions of initial condition sensitivity for weather forecasts.

Stratospheric Satellites

The Global Air-ocean IN-situ System (GAINS) will consist of a dynamic constellation of 400 vehicles having an average spacing of one vehicle every 10° latitude by 10° longitude. Observations of atmospheric, air chemistry and oceanic variables are made over ocean and remote regions by releasing sondes from the vehicle's float altitude in the upper troposphere/lower stratosphere. GAINS vehicles consist of three types. In polar regions of the winter hemisphere, ~40 fueled ROA (remotely-operated aircraft, such as the Global Hawk developed for the Air Force) fly at 20 km for week-long periods. In the midlatitudes of the winter hemisphere, ~80 solar powered ROA (e.g., the AeroVironment Pathfinder) perform the same function for longer periods. In the subtropics of the winter hemisphere and the entire summer hemisphere, ~280 superpressured balloons, floating between 18 and 22 km for several months, complete the constellation. The full-scale, 33-m-diameter, superpressure balloons will carry a 400-kg payload, which includes 500 hundred metsondes. GAINS has focused on development of the superpressure balloon vehicle and computer simulation of management of the 400-vehicle network.

GAINS

B.8 Bi-Directional RAOB

Advances in the capabilities of data assimilation systems and their implementation in conjunction with numerical weather prediction have raised the question of ingesting radiosonde observations after balloon burst -- during the descent phase. It is possible now in research models to routinely ingest RAOBs at non-standard times and locations.

In effect, a descending radiosonde provides PTU and wind data at non-standard times and locations. Although this in principle is a simple, attractive and economical concept, its successful implementation will require significant development and testing. Vaisala is currently addressing issues pertaining both to data availability and data quality from descending sondes. In the early stages of development, focus is on the use of only a single receiver that is located at or near the launch station. In the case of nearby terrain blocking, Vaisala currently offers as a standard product a remote antenna capability that allows the receiving antenna to be located on the intervening terrain or on a tall tower. Future capability will also include the ability to receive data from the sonde at multiple receiver locations (these could be adjacent standard RAOB launch sites or special receive-only sites), and a composite profile could then be reconstructed from partial data sets available at different receiver locations.

Bi-Directional RAOB

B.9 Lidar

The proposed Doppler Lidar Technology Accelerator Program will lead to the development of two airborne (ultimately space-based) wind lidar systems capable of operating separately or together in a coordinated or hybrid fashion. The first system is an extension of work being performed at NASA GSFC (which has a mobile ground-based system in operation now) and is based on molecular backscatter, the second system is a coherent Doppler lidar in development at MSFC, NASA Langley and JPL which would measure winds from aerosol backscatter. The two systems together would be capable of measuring wind profiles from the surface to 20 km with the molecular system providing clear air winds in regions of low aerosol (free troposphere and lower stratosphere) and the aerosol system providing high accuracy winds in the PBL and from clouds. The target aircraft for the molecular system would be the NASA ER-2 and the for the coherent system the DC-8. Both would fly together in hybrid mode on the DC-8. If funded, the systems would be available on aircraft in the 2004-05 time frame.

Lidar efforts underway at NOAA/ETL could have direct application to THOR*pex* objectives. A high-resolution wind lidar will be deployed during the upcoming

International H_2O Project on a DLR Falcon alongside a DLR water vapor lidar to remotely measure vertical flux profiles and horizontal transport of low level water vapor. Plans call for this instrument to be subsequently modified for operation in a C-130 or P-3 wing fuel pod. Lidar aerosol and ozone profiles can also be applied to determine tropopause height and characterize cloud levels to improve height assignments of satellite cloud track wind estimates.

B.10 Smart Balloon

A new generation of smart (constant volume adjustable density) balloons can provide high time resolution (~1 hr) observations of temperature, pressure, and humidity in the lower troposphere. Development of this platform is made possible by recent technical advances, including lightweight affordable satellite telephones, improvements in balloon and transponder design, better instrument accuracy, altitude control system, and improvements in GPS receivers. The smart balloon is frangible and its relatively small size (~3.5 m in diameter) and low weight minimize potential concerns about airspace regulations.

"Smart" Balloon

B.11 Ocean Surface-Data Buoy

Observations of sea-level pressure, sea-surface temperature, and other parameters from remote ocean locations can be provided by relatively inexpensive (~ $20K) moored buoys transmitting data to the GTS in near real-time on an hourly basis through GOES or other commercial satellites. The objective is to develop a platform that can last for at least 2-3 years, with the eventual goal of providing a cost-effective array for the North Pacific. This buoy system is being developed by the Engineering Development Division of NOAA’s Pacific Marine Environmental Laboratory (PMEL), which also developed and maintains the equatorial TAO buoy array. Preliminary stages in the design of the data processing unit, buoy, and mooring line were initiated in June 2000. Ultimately, a network of buoys (~ 50) could be deployed over large expanses of the North Pacific. In addition, Russia is adding 3-4 drifting or fixed ocean buoys each year from 2001 to 2004 in its arctic regions.

B.12 Buoy-Mounted Profiler

The first field test of a buoy-mounted radar wind profiler on a Scripps Marine Observatory buoy was conducted during March 2000 by the NOAA Environmental Technology Laboratory (ETL). This is a step toward adding an atmospheric profiling capability to buoys, which, when combined with subsurface measurements, could provide vertical profiling through both the oceanic and atmospheric boundary layers. Further testing and evaluation of this prototype system is on-going.